2009年度GCOEフロンティアセミナー

精密単独測位の技術動向と応用

Precise Point Positioning (PPP) and Its Applications

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Precise Point Positioning (PPP)

Precise Point Positioning (PPP)

- Typical Analysis Strategy
  - Zero-Differenced (ZD) Measurement Equations
  - Precise Satellite Orbit/Clock: IGS or Others
  - Ionosphere: Eliminated by Ionosphere-Free LC
  - Troposphere: ZTD or ZWD Estimation + Mapping Function
  - Antenna Model, Earth-Tides, Phase Wind-up Corrections
  - Float Estimation of Carrier-Phase Ambiguity
- Reference
  - J.F. Zumberge et al., Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks", *JGR, Vol. 102, No. B3*, 1997

Features and Applications

- Feature
  - with Single Receiver (No Reference Station)
  - Efficient Analysis for Many Receivers
  - Absolute Position in ITRF Frame
- Applications
  - Crustal Deformation Monitoring
  - GPS Seismometer
  - GPS Meteorology
  - POD (Precise Orbit Determination) of LEO Satellite
  - Precise Time Transfer

Limitations of Conventional PPP

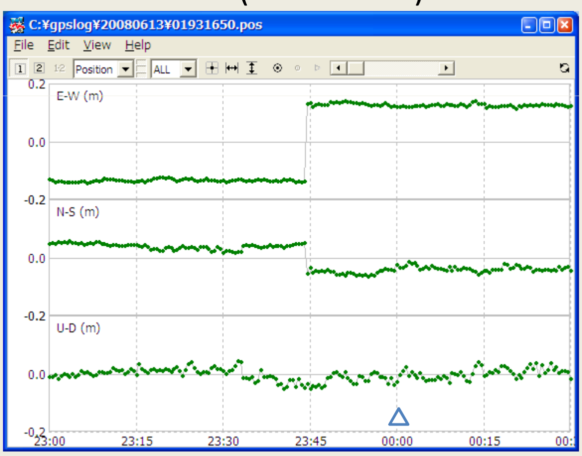
- Accuracy/Precision
  - Depend on Quality of Precise Satellite Orbit/Clock
  - Satellite Clock Interpolation Error/Day-Boundary Problem
  - Solution Drift by Float Ambiguity and Imperfect Correction
- Real-time Processing
  - Lack of Real-time Precise Satellite Clock
- Long Convergence Time
  - Due to Float Ambiguity Estimation
- Inaccurate with Single-Freq Receiver
  - Poor Ionospheric Correction Model

KGPS vs Kinematic-PPP

Displacement by Iwate-Miyagi EQ

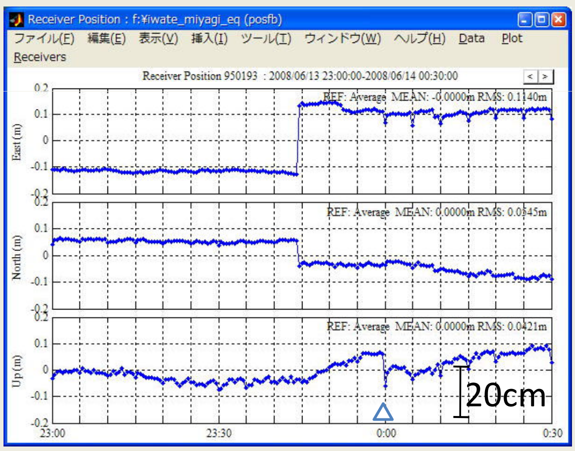
2008/6/13 22:00-6/14 0:30, GSI 0193 Minase

KGPS (BL=219 km)



by RTKPOST 2.2.1

Kinematic-PPP



IGS Final Orbit/30-s Clock

by GT 0.6.4

△ :Day-Boundary

IGS Orbit/Clock

IGS Prduct Table

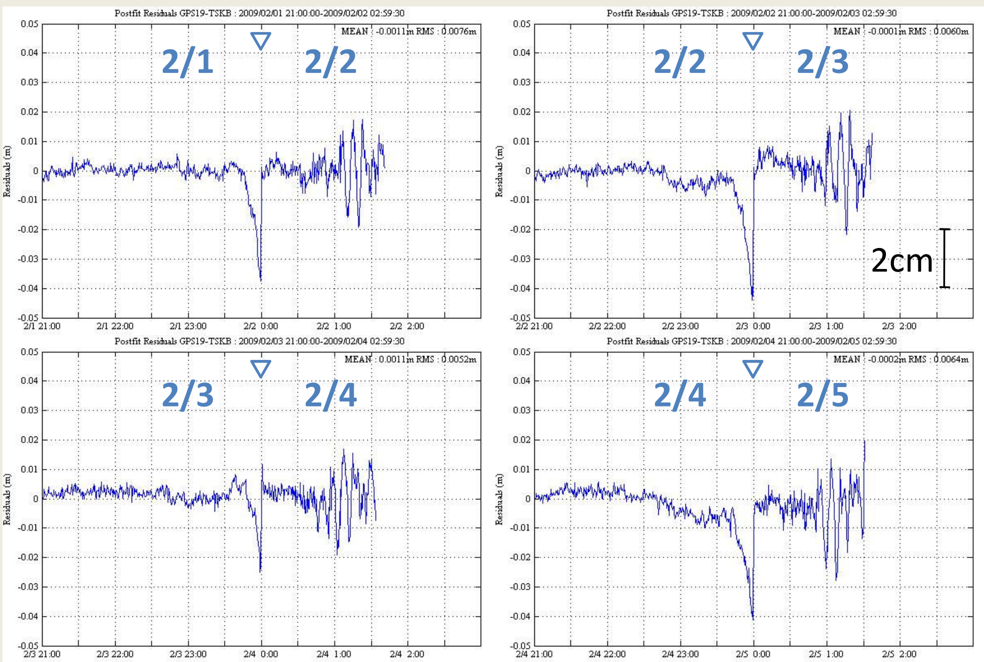
		Final (IGS)	Rapid (IGR)	Ultra-Rapid (IGU) Observed	Ultra-Rapid (IGU) Predicted	Broadcast
Accuracy	Orbit	~2.5cm	~2.5cm	~3cm	~5cm	~100cm
	Clock	~75ps RMS ~20ps STD	~75ps RMS ~25ps STD	~150ps RMS ~50ps STD	~3ns RMS ~1.5ns STD	~5ns RMS ~2.5ns STD
Latency		12-18 days	17-41 hours	3-9 hours	realtime	realtime
Updates		every Thursday	at 17 UTC daily	at 03, 09, 15, 21 UTC	at 03, 09, 15, 21 UTC	-
Sample Interval	Orbit	15min	15min	15min	15min	daily
	Clock	Sat: 30s Stn: 5min	5min	15min	15min	daily

(2009/8, http://igscb.jpl.nasa.gov/)

Day-Boundary Problem

Static-PPP Residuals

2009/2/1-2/4 , PRN19 - TSKB, IGS Final Orbit/Clock

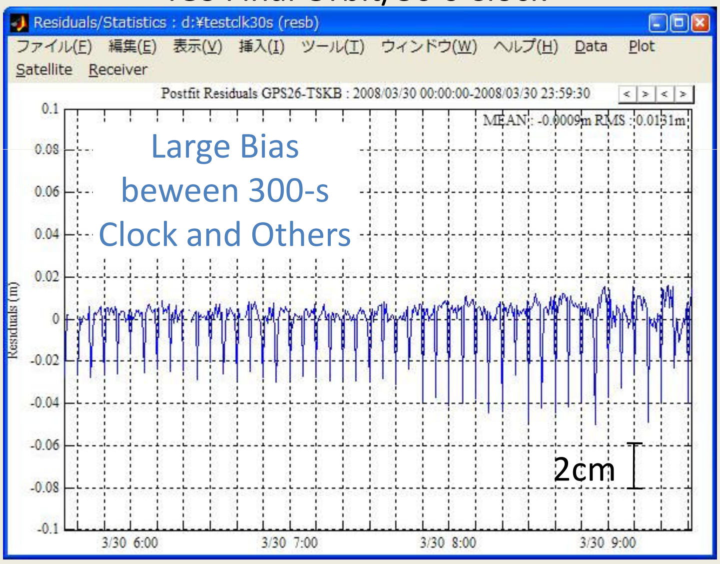


Anomaly of IGS 30-s Clock

Static-PPP Residuals

2008/3/30 5:35-9:30, PRN26 - TSKB

IGS Final Orbit/30-s Clock



IGS AC Orbit/Clock

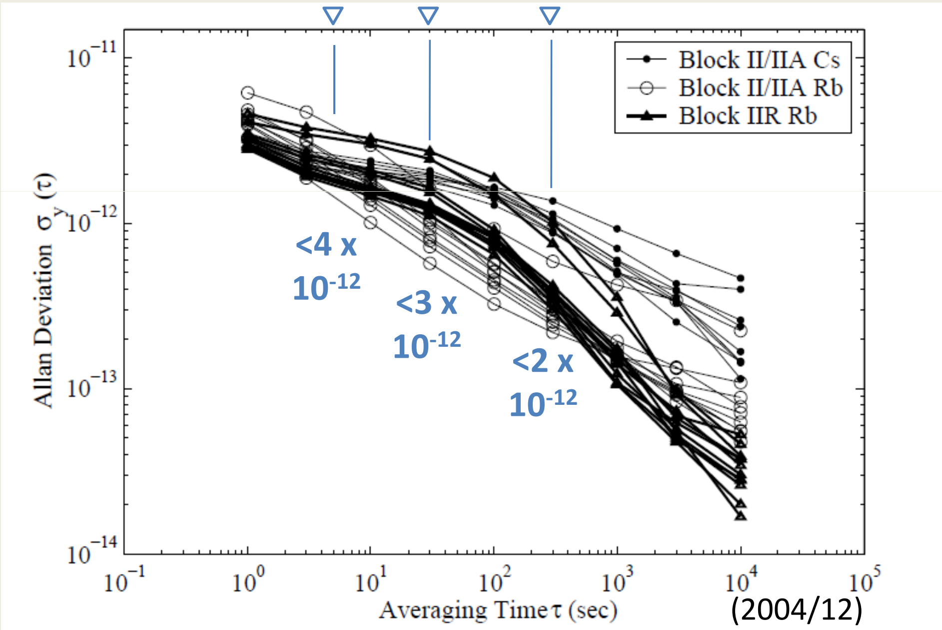
AC	Final		Rapid		Ultra-Rapid	
	Orbit	Clock	Orbit	Clock	Orbit	Clock
CODE	15min	**5s/30s**	15min	5min	15min	15min
ESOC	15min	5min	15min	5min	15min	15min
GFZ	15min	5min	15min	5min	15min	15min
JPL	15min	5min	15min	5min	-	-
NOAA	15min	15min	15min	15min	-	-
NRCan	15min	**30s**	15min	5min	15min	15min
SIO	15min	-	15min	-	15min	15min
USNO	-	-	-	-	15min	15min
MIT	15min	**30s**	-	-	-	-
GRG	15min	5min	-	-	-	-
USN	-	-	15min	5min	-	-
GOU	-	-	-	-	15min	15min

(2009/8, http://igscb.jpl.nasa.gov/)

Interpolation Error of Clock

Satellite Clock Stability

5s 30s 300s



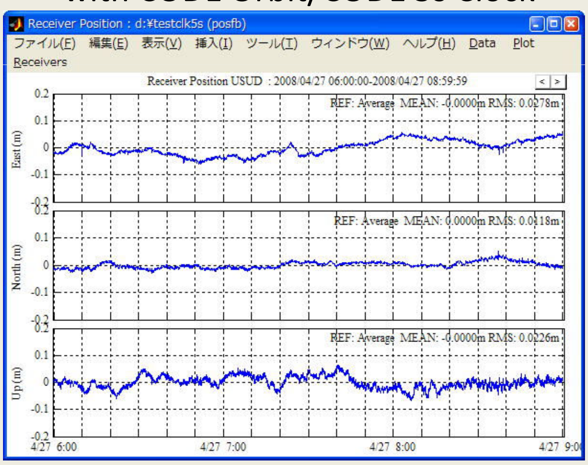
CODE 5-s Clock

S.Schaer, [IGSMAIL-5771] Model changes made at CODE, 14 May 2008

H.Bock et. al., High-rate GPS clock correction from CODE: support of 1Hz applications, *J Geod.*, 2009

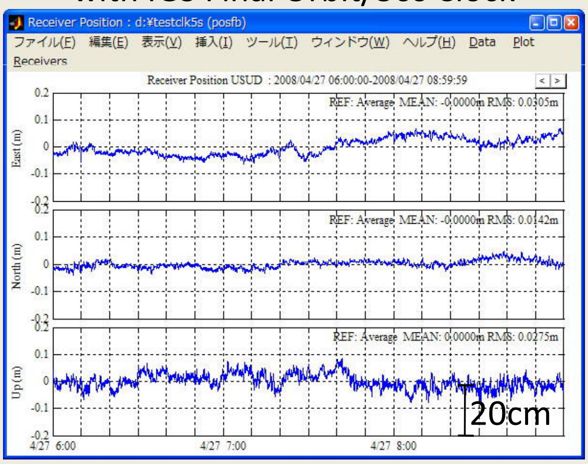
1Hz Kinematic-PPP 2008/4/27 6:00-9:00 IGS USUD

with CODE Orbit/CODE 5s Clock



RMSE: E: 2.78cm N: 1.18cm U: 2.26cm

with IGS Final Orbit/30s Clock



RMSE: E: 3.05cm N: 1.42cm U: 2.75cm

Real-Time PPP

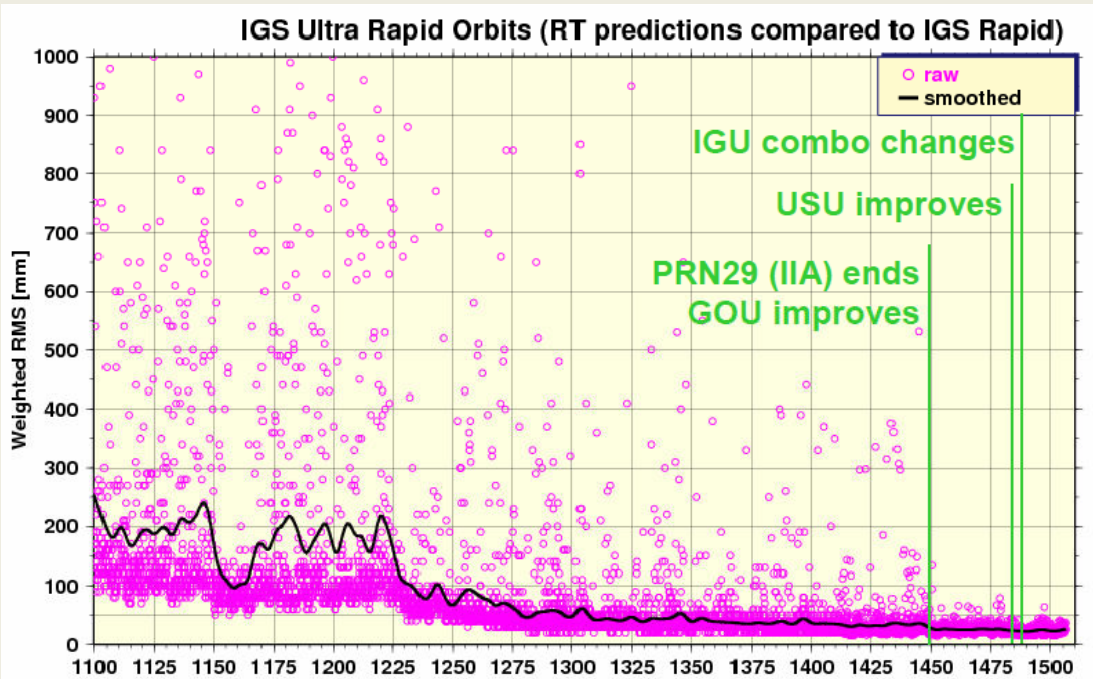
Real-Time PPP

- Strategy 1:
  - Orbit/Clock: Estimated in Real-Time
  - Need World-Wide Station Network (>50 Stations)
  - Complicated Processing Process
  - CPU Load Restriction
- Strategy 2:
  - Orbit: Fixed to IGU-Predicted
  - Clock: Estimated in Real-Time
  - Regional Station Network
  - Simple Processing Process

StarFire^{TM}

- Features
  - Commercial Service by NavCom
  - Broadcast Real-Time Orbit/Clock via Satellite (Inmarsat)
  - JPL RTG (Real-time GIPSY) Processing Engine (GDGPS)
  - World Wide Station Network (72 Stn in 2006)
  - Ionosphere: L1/L2 Dual-Freq
  - Troposphere: WAAS Model
  - QC by Real-Time Monitor for Satellite Anomaly
- Accuracy/Precision
  - Horizontal Position RMS: <10 cm

Improvement of IGU Orbit



(J.Ray et. al., Status of IGS Ultra-Rapid Products for Real-Time Applications, 2008 AGU Fall Meeting)

IGU Orbit + Clock Est + PPP

- RTnet
  - Developed by GPS Solutions (http://www.gps-solutions.com)
- CDAAC
  - Near Real-Time POD of LEO Satellites (COSMIC ...)
  - Bernese 5.0
- EUREF NRTK Service
  - Use RTnet
  - Provide Real-Time Orbit/Clock via Internet (NTRIP)
- JMA
  - Near Real-Time GEONET PWV for NWM

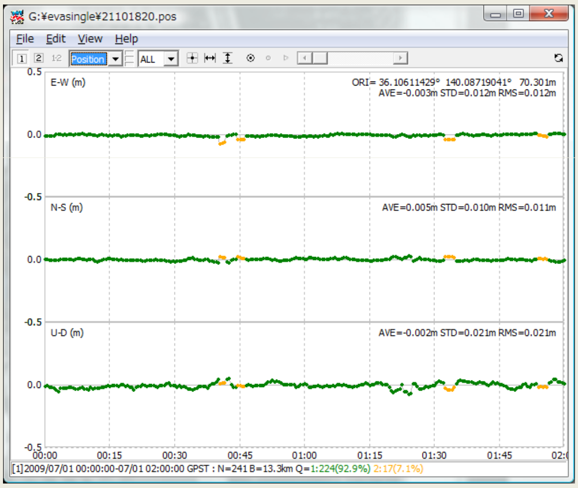
PPP-AR

Convergence Time of PPP

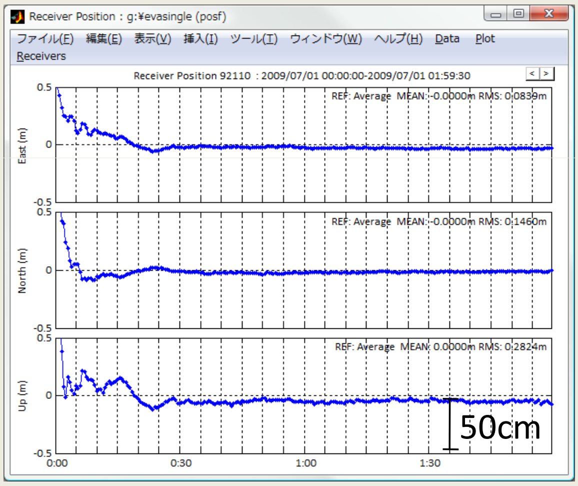
Kinematic Solution

2009/7/1 0:00-2:00, GSI 2110

KGPS with AR (BL=13.3km) | Kinematic-PPP



by RTKPOST 2.2.1



by GT 0.6.4,
IGS Final Orbit/CODE 5-s Clock

PPP-AR

- with AR for PPP
  - Improve Convergence Time
  - Improve Accuracy of Static Solution (EW, UD)
  - Improve Stability of Kinematic Solution
- Difficulties of AR for PPP
  - Unknown Satellite Initial Phase Biases
  - Effect of Precise Orbit/Clock Error
  - Effect of Ionospheric Delay
  - Code/Phase Bias Instability
  - Multipath Effect at Reference Station Network

Research

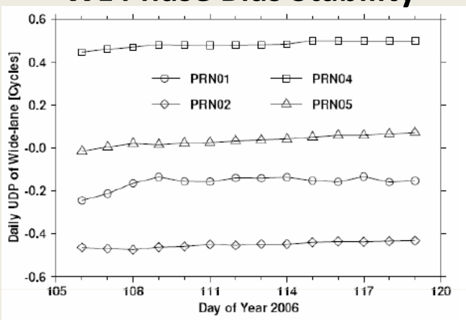
- •M.Ge et al., Resolution of GPS carrier-phase ambiguities in Precise Point Positioning (PPP) with daily observations, Journal of Geodesy, 2007
- •D.Laurichesse et al., Integer ambiguity resolution on undifferneced GPS phase measurements and its application to PPP, ION GNSS 2007
- •G.Weber et al., Real-time Clock and Orbit Corrections for Improved Point Positioining via NTRIP, ION GNSS 2007
- •D.Laurichesse et al., Real Time Zero-difference Ambiguities Fixing and Absolute RTK, ION NTM 2008
- •P.Collins, Isolating and Estimating Undifferenced GPS Integer Ambiguity, ION NTM 2008
- •J.Delporte et al., GPS Carrier-Phase Time Transfer Using Single-Difference Integer Ambiguity Resolution, International Journal of Navigation and Observation, 2008
- •J. Geng et al., Performance of Hourly Precise Point Positioing with Ambiguity Resolution, ION GNSS 2008
- •P.Collins et al., Precise Point Positioning with Ambiguity Resolution using the Decoupled Clock Model, ION GNSS 2008
- •D.Laurichesse et al., Zero-differnce Ambiguity Fixing for Spaceborne GPS Receivers, ION GNSS 2008
- •L.Mervart et al., Precise Point Positioning With Ambiguity Resolution In Real-Time, ION GNSS 2008
- •C.Rocken et al., Precise Positioning of Ships and Buoys in the Open Ocean - Result from a 3-month Indian Ocean Cruise, and Tsunami Buoy Off Japan's Coast, ION GNSS 2008
- •T.Iwabuchi et al., Deformation Monitoring with Single Frequency L1 Receivers, ION GNSS 2008

PPP-AR Strategy/Application

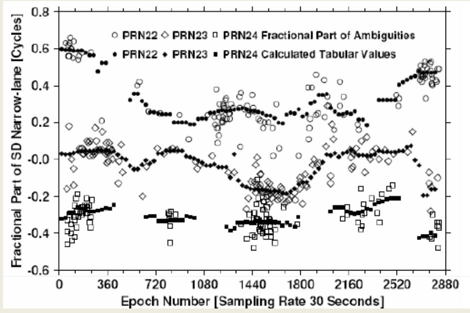
- Typical Strategy
  - Post Processing, Few Research for in Real-Time
  - Use Global Reference Stations Network
  - Fix Narrow-Lane Ambiguity with Iono-Free LC after Fixing Wide-Lane MW LC
  - Estimate Satellite Initial Phase Bias Assuming its Stability
  - PPP with Initial Phase Bias Correction
- Application
  - Precise Network Coordinates by Static-PPP
  - LEO Satellite POD, ...

M.Ge et al., EGU 2007

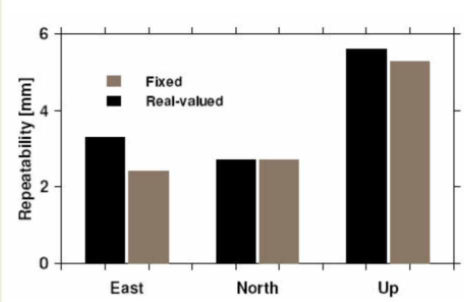
WL Phase Bias Stability



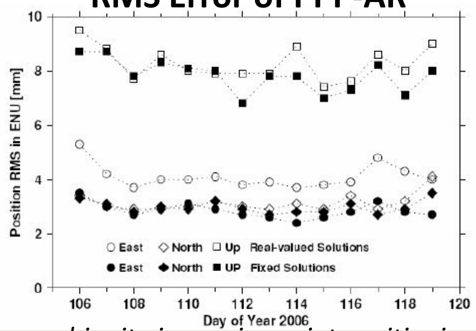
NL Phase Bias Stability



Repeatability of PPP-AR



RMS Error of PPP-AR



M.Ge et al., Resolution of GPS carrier-phase ambiguity in precise point positioning, EGU Assembly 2007

PPP-RTK

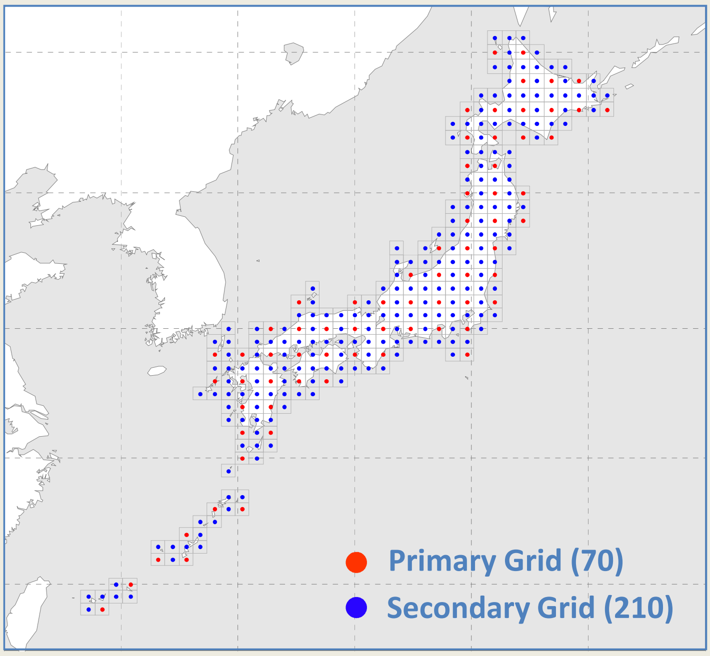
PPP-RTK

- Two View Points
  - Widely Extended NRTK (Network RTK)
  - Real-Time Kinematic PPP with AR
- Feature
  - State Space Correction Data
  - Satellite Code/Phase Bias Corrections for AR
  - Ionospheric Model for Single-Freq Users
  - Minmum Band-Width for Broadcast Communication Link

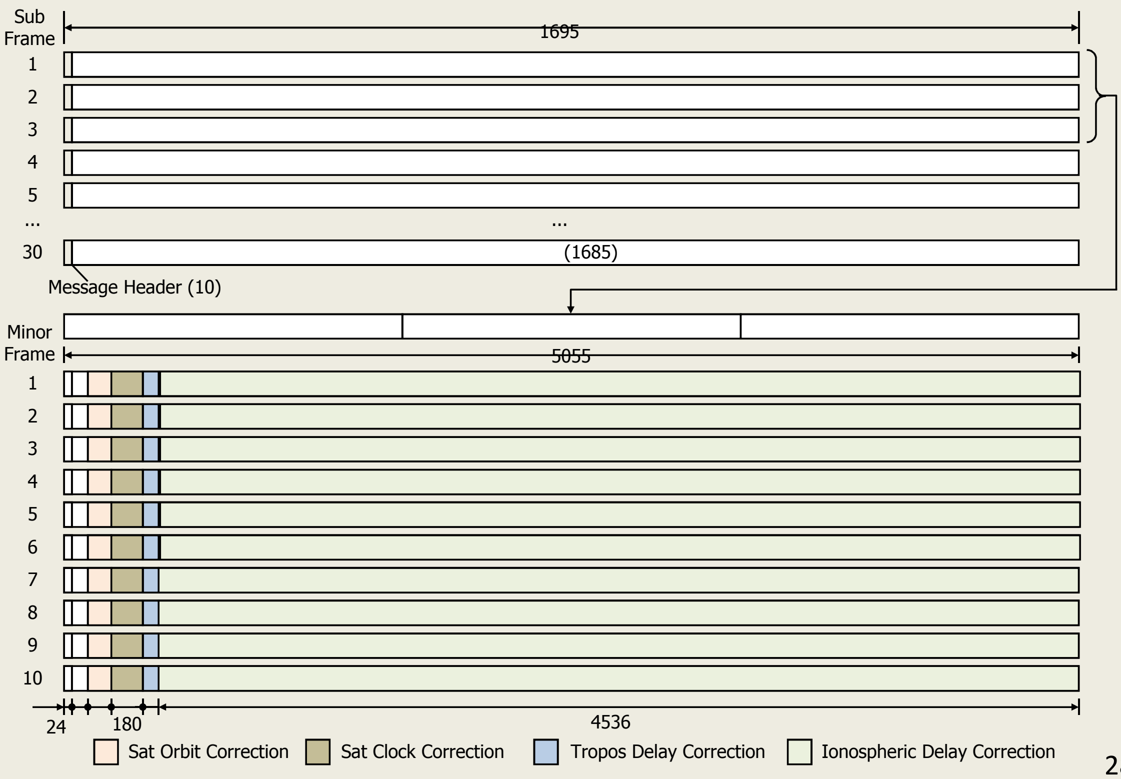
PPP-RTK via QZS LEX

Corrections	Bits	LSB	Range	# Sat	# Grid	Interval	bps
Sat Orbit	15×3	2mm	-33-33m	12	-	30s	**18**
	15×3	.02mm/s	-.3-.3m/s	12	-	30s	**18**
Sat Clock	15	0.006ns	-98-98ns	12	-	3s	**60**
Ionos Delay	15	2mm	0-66m	12	70	30s	**420**
	13	2mm	-8-8m	12	210	30s	**1092**
Tropos Delay	11	0.5mm	0-1m	-	70	30s	**26**
Phase Bias	11×3	0.01cyc	-10-10cyc	12	-	30s	**13**
Code Bias	8×3	0.1m	-13-13m	12	-	30s	**10**
Sat ID+IOD	8+8	-	-	12	-	30s	**6**
Others	-	-	-	-	-	1-30s	**32**
Total							**1695**

Correction Grid



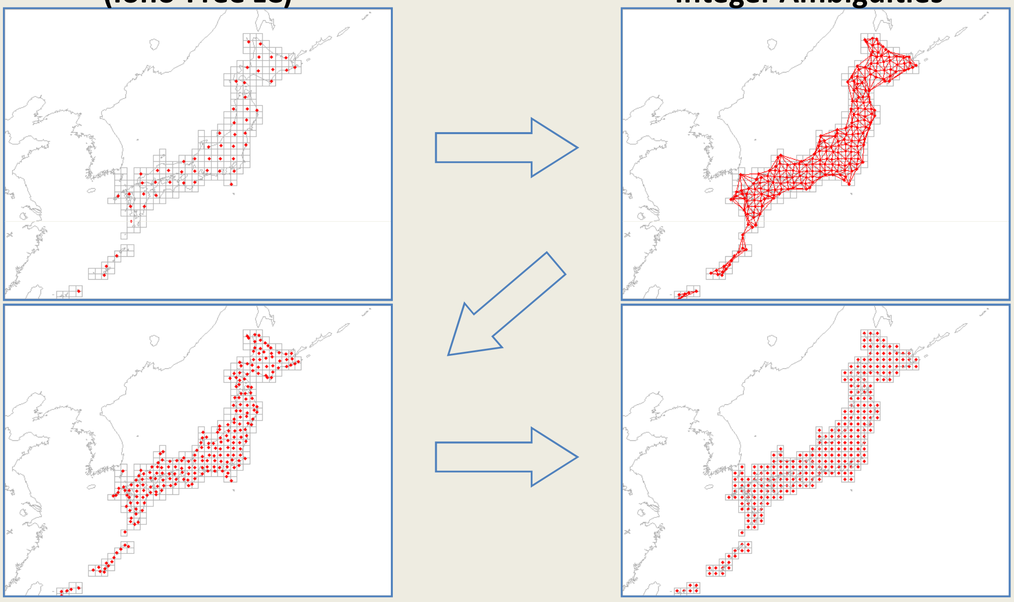
Message Format



Correction Generation

(1) Orbit/Clock/Tropos Estimation (Iono-Free LC)

(2) Ionos/Tropos Estimation, Fix Integer Ambiguities



(3) Orbit/Clock/Tropos/Ionos/Bias Re-Estimation

(4) Interpolate Ionos/Tropos Deley to Grids

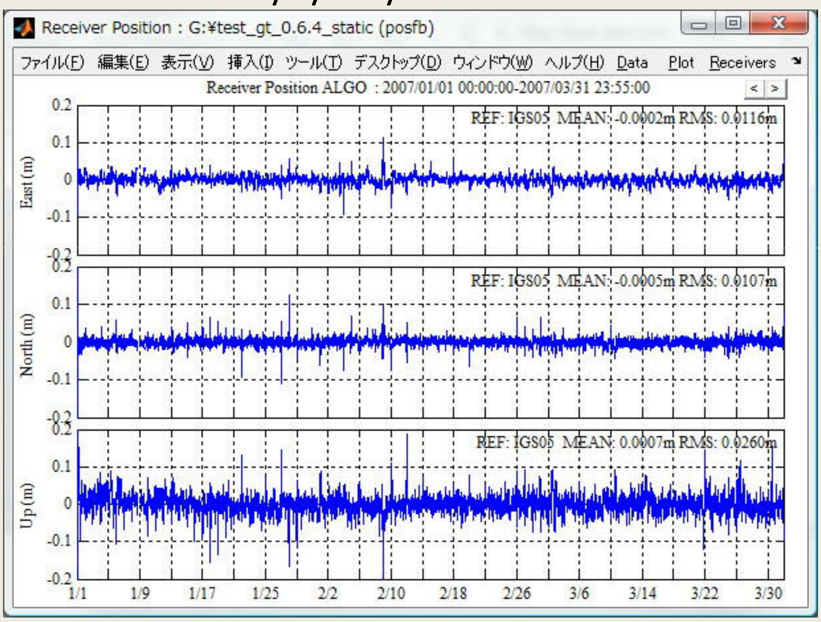
GT 0.6.4

GT 0.6.4

- 2009/5/1 Release
  - Open Source License (GPLv3)
  - Matlab 7.3 (R2006b) or Higher, 32bit or 64bit
- GT 0.6.3 -> 0.6.4
  - Support High Rate Analysis up to 100 Hz
  - Support Long Continuous Session up to 1 year
  - Support IGS 30-S, CODE 5-s, IGS/CODE 5-s Clock
  - Support IGS05, ITRF2005 Frame
  - Support VMF1 and GPT Meteo Model
  - Support Az Term of Receiver Antenna PCV

Stability of Kinematic-PPP

2007/1/1-3/31 IGS ALGO

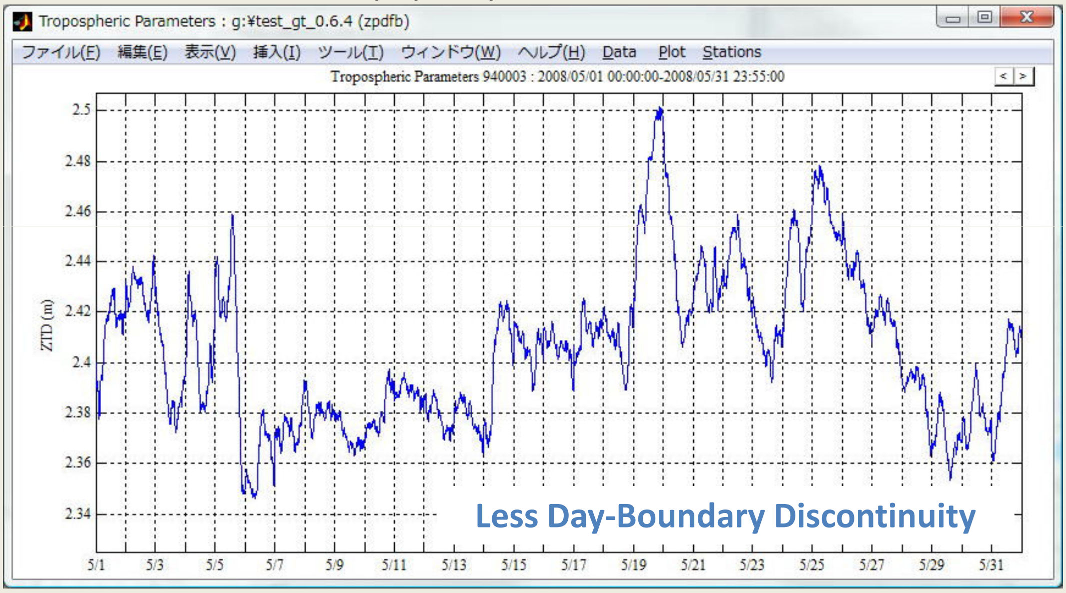


with IGS Final Orbit/Clock

RMS Error:
E: 1.16cm
N: 1.07cm
U:2.60cm

Long Session ZTD

2009/5/1-5/31 GSI 940003

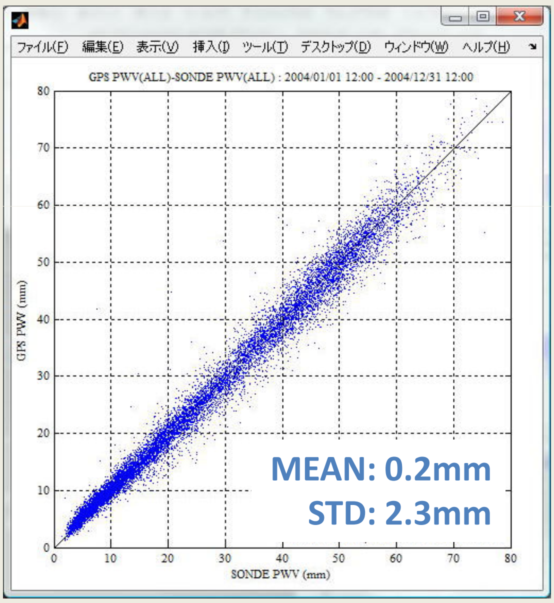


with IGS Final Orbit/Clock

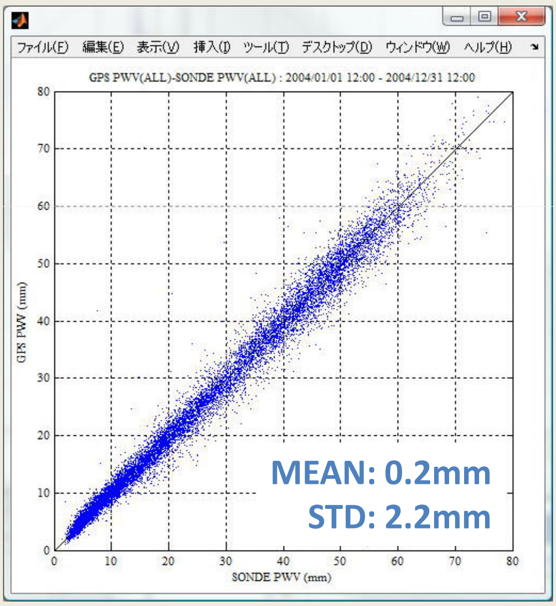
NMF vs VMF1

Sonde PWV - GPS PWV: GSI 19 Stns, 2004/1/1-12/31

NMF



VMF1



with IGS Final Orbit/Clock